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A New Silurian Graptolite Locality in the Central Maine/Aroostook-Matapedia Basin, Northeastern Maine

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INTRODUCTION

The lithostratigraphic framework of Maine consists of several northeast-trending belts of Cambrian to mid-Ordovician metasedimentary and metavolcanic "basement" rocks separated by broad swaths of mostly metasedimentary Late Ordovician through Early Devonian cover strata (Figure 1). The Central Maine/ Aroostook-Matapedia (CMAM) basin is the largest of these cover rock belts, extending from the New Hampshire border in southwestern Maine to the eastern and northeastern parts of the state, and into western and central New Brunswick.

Formations consisting largely of turbiditic sandstone underlie most of the basin, but fossils are extremely rare and the ages of the sandstone units are poorly constrained. Figure 2 shows areas within the CMAM basin from which fossil-based age control has been reported. Graptolites are the most common fauna, with numerous sites in the southwestern (Osberg, 1988; Ludman 1976; Ludman and Griffin 1974; Pankiwskyj et al., 1976) and northeasternmost (Pavlides and Berry, 1966) areas. In addition, chitinomorphs and acritarchs were discovered recently (Ludman et al., 2020) in the east-central part of the basin.

Previous Work

The stratigraphy of relevant parts of the CMAM basin is based on detailed mapping in the key areas shown in Figure 2, and correlations among these sections are shown in Figure 3. Cross-strike and strike-parallel variations revealed by comparing sandstone distribution (Figure 3) with section locations (Figure 2)

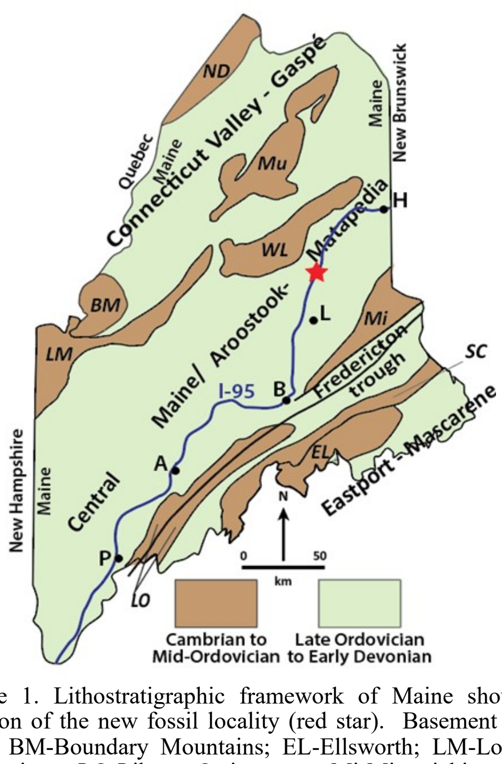

Figure 1. Lithostratigraphic framework of Maine showing location of the new fossil locality (red star). Basement rock belts: BM-Boundary Mountains; EL-Ellsworth; LM-Lobster Mountain; LO-Liberty-Orrington; Mi-Miramichi; Mu-Munsungun; ND-Notre Dame; SC-St. Croix; WL-Weeksboro-Lunksoos. Cities: A-Augusta; B-Bangor; H-Houlton; L-Lincoln; P-Portland.

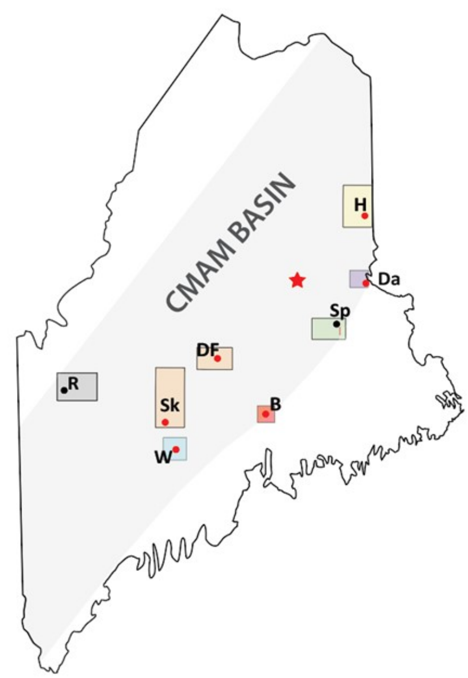

Figure 2. Simplified map of the CMAM basin showing locations of key stratigraphic sections described in Figure 3. CMAM label parallels the dominant regional structural trend. Red star is location of the new graptolite locality. Red dots indicate fossil age control, black dots the absence of fossil data. Stratigraphic sections shown in Figure 3: B-Bangor; Da-Danforth; DF-Dover-Foxcroft; H-Houlton; R-Rangeley; Sp-Springfield; Sk-Skowhegan; W-Waterville.

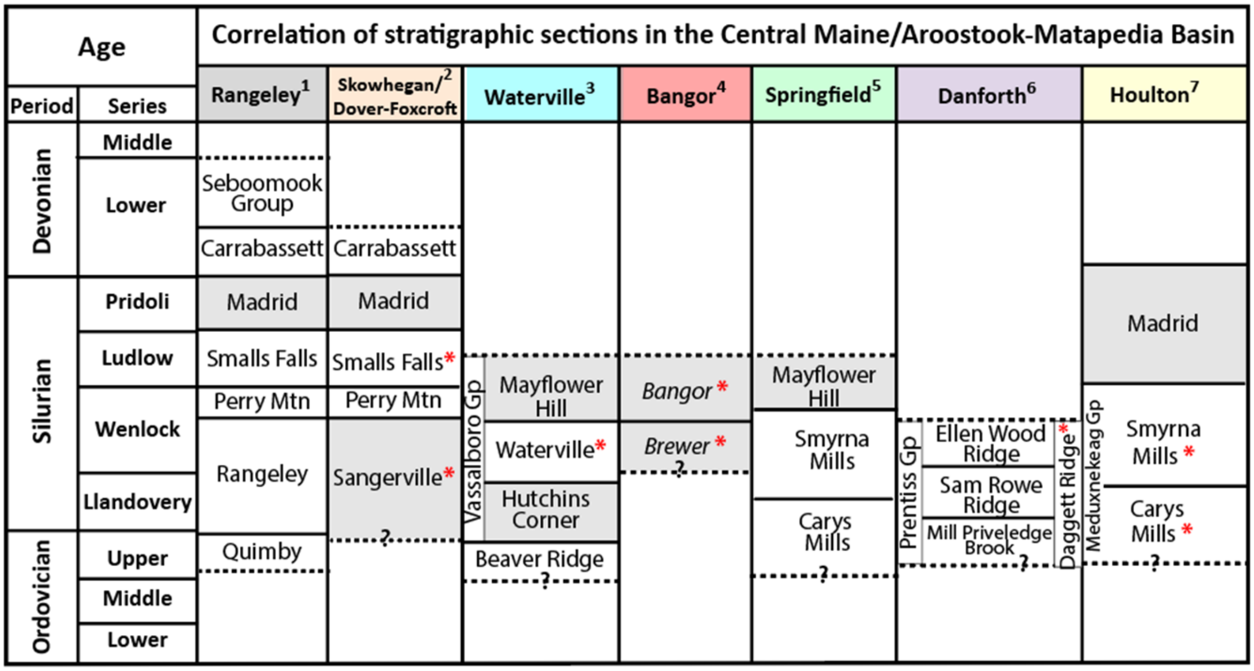

Figure 3. Correlation of key stratigraphic sections in the CMAM basin. Shading highlights formations composed dominantly of sandstone. Asterisks indicate fossils reported in previous studies. Sources: 1- Moench and Pankiwskyj, 1988; 2-Ludman and Griffin, 1974; Pankiwskyj et al., 1976; 3-Osberg, 1988; Marvinney and et al., 2010; 4-Pollock, 2011a, 2011b; Ludman, et al., 2020; 5-Ludman and others, 2017; 6-Hopeck 1998; 7-Pavlides, 1968, 1971; Ludman and Hopeck, unpublished mapping).

are interpreted as facies changes resulting from basinward and axial currents associated with emergent source areas within the basin (summarized by Ludman et al., 2017, 2020).

Each of the sections shown in Figure 2 is the product of years of detailed mapping, but the new locality is in an area known only from reconnaissance studies by Roy (1981), Ekren and Frischknecht (1967), and Neuman (1967). Correlations are tenuous because of the scarcity of fossils, and for many years a single graptolite site near the new locality was the only faunal age evidence between Houlton and Dover-Foxcroft (Roy and Forbes, 1970). The fossils were in a black shale horizon interpreted as the contact between the provisional Allsbury and Lawler Ridge formations (Roy, 1981) – the same horizon as the new locality – although the current stratigraphic interpretation is different (see Discussion below).

W.B.N. Berry described the graptolites at the previously known site as “badly deformed, ... either pulled out or squashed ... ", and identified them tentatively as “Monograptids of the *M. dubius* group (M. praedubius Boucek?), *Monograptus priodon* (Bronn)?, and *Monograptus sp* (Monograptus of the *M. nudus* group?)” (*in* Roy and Forbes, 1970). Despite the fact that “I can't put any exact names on the forms present", he assigned a Late Llandovery age to the assemblage, “probably in the span of Ellis and Wood zones 24- 25”.

The previously known outcrop was revisited in the summer of 2020, but has degraded badly in the past 50 years and no fossils were detected. The new locality was discovered later that day and it was hoped that better preservation of its graptolites would permit more confident identification and more precise dating.

THE NEW GRAPTOLITE LOCALITY

Site Description

Location: UTM (Zone 19) 0542015 E 5065856 N (NAD 27); Salmon Stream Lake 7½' quadrangle.

The new fossil locality is a roadcut 12-15 feet high in the I-95 southbound median strip (Figure 4), between the Benedicta and Medway exits just south of milepost 255. To reach the site from the south, take Exit 259 (Benedicta) from I-95, turn left off the exit ramp, and left again immediately to return south on I-95. There is no northbound re-entry at this exit. ***Please note that stopping or parking along the interstate is not allowed.***

The site is close to the northern limit of greenschist facies metamorphism in Maine (Guidotti *in* Osberg et al., 1985), and a faint sheen on cleavage surfaces indicates weak recrystallization. An estimated maximum temperature of 300°C is suggested for the original site based on vitrinite reflectance (M. Malinconico, personal communication, 2021) and the state of microfossil thermal maturation (P. Fernandes and G. Machado, personal communication 2021).

Most of the outcrop (>95%) consists of strongly

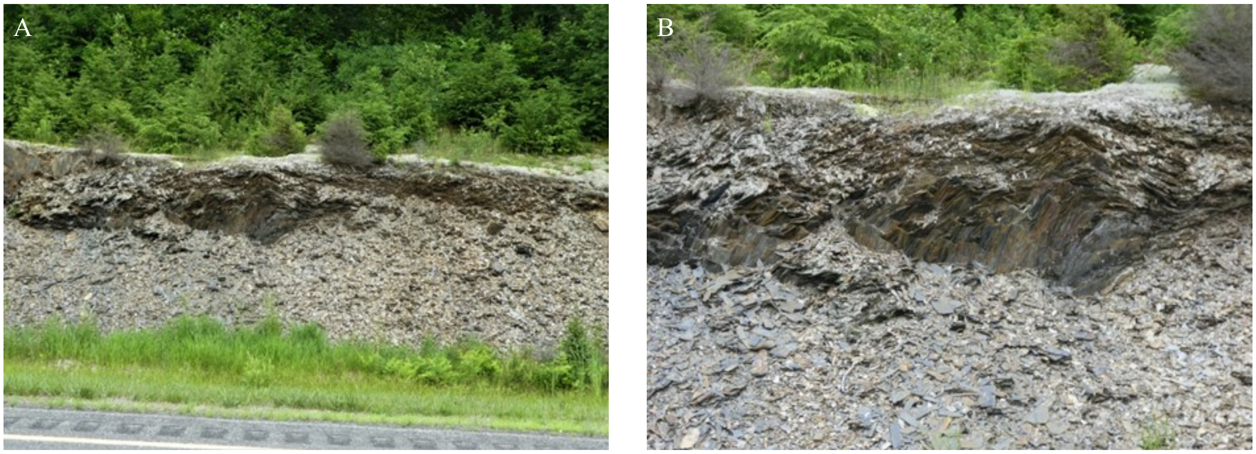

Figure 4. The fossil locality, looking southeast across the southbound lanes of I-95. (a) overview, (b) close-up showing slumping at top of outcrop and abundant graptolite-bearing black shale cleavage plates in the talus.

cleaved black carbonaceous shale with very subordinate beds of sulfidic sandstone and coarse siltstone 1-5 centimeters (cm) thick. The shales do not exhibit rusty weathering although cubic holes up to 8 millimeters (mm) on a side indicate the former presence of large pyrite crystals. In contrast, the sandstones and siltstones contain abundant small pyrite crystals and develop a thick rusty weathering rind.

Bedding is parallel to cleavage at the top of the roadcut, dipping steeply and striking 015°, nearly parallel to the I-95 roadway, but are slumped locally and covered by an extensive talus deposit at the base (Figure 4b). Cleavage plates of black shale a few millimeters thick make up most of the talus pile, along with some thicker 8 mm - 2 cm cleaved slabs and thicker slabs of sandstone. A stretching lineation is well developed in some samples, requiring that care be taken in faunal identification because of differential distortion depending on fossil orientation relative to the lineation (see below).

Graptolite Preservation

Graptolites in this collection are preserved as fully compressed carbonaceous films that stand out clearly from the less reflective background. The specimens show very conspicuous evidence of tectonic strain, particularly stretching in the direction of the mineral lineation visible on the bedding/cleavage planes.

FAUNAL IDENTIFICATION AND AGE

Although most of the specimens exhibit the general thecal and rhabdosomal form typical of species of the *Pristiograptus dubius* group, identification to the species level relies on measurements of rhabdosomal width and thecal spacing as well as observation of details of the apertural form of the sicula and proximal theca. Among the hundreds of rhabdosome fragments present in the collection four specimens were found showing well-preserved proximal ends. Of those four specimens, two show three distinctive attributes of the proximal end: distinctly convex and slightly flared (lobate) apertures on the first two to three thecae; a slightly ventrally curved sicula with a thick virgella that projects slightly outward, followed by a weak downward bend; and a very strong dorsal tongue or rutellum on the sicular aperture that points downward, producing strongly concave sicular aperture (Figs. 5a.2, 5a.3 – see Appendix for morphologic terminology). One specimen shows the slightly lobate proximal thecae, but the details of the sicular aperture are not completely preserved (Fig. 5a.4). The other specimen with a well-preserved proximal end shows no evidence of the modified apertures on the first few thecal pairs or the strong rutellum on the sicular aperture (Fig. 5a.1).

Graphical Retrodeformation

In order to better compare the specimens preserved in different orientations with respect to tectonic strain and identify the species in this collection, an attempt has been made to graphically “retrodeform” the specimens (e.g., Williams, 1990). In order to do this, camera lucida drawings were made of a number of specimens preserved together on bedding planes, noting the angle of orientation of the specimens relative to the direction of maximum extension, indicated by the mineral lineation. The drawings were traced in Adobe Illustrator and were assembled onto a single page, all aligned to the same direction of elongation (Fig. 5a). One of the two key bedding planes that preserves most of the best specimens was also photographed (Fig. 6a). For both the composite drawing and the bedding plane photo, the files were opened in Adobe Photoshop and the images were shortened along the direction of the mineral lineation to the point where all of the similar-looking specimens showed closely similar values of rhabdosomal width and thecal spacing (Figs 5b, 6b). This

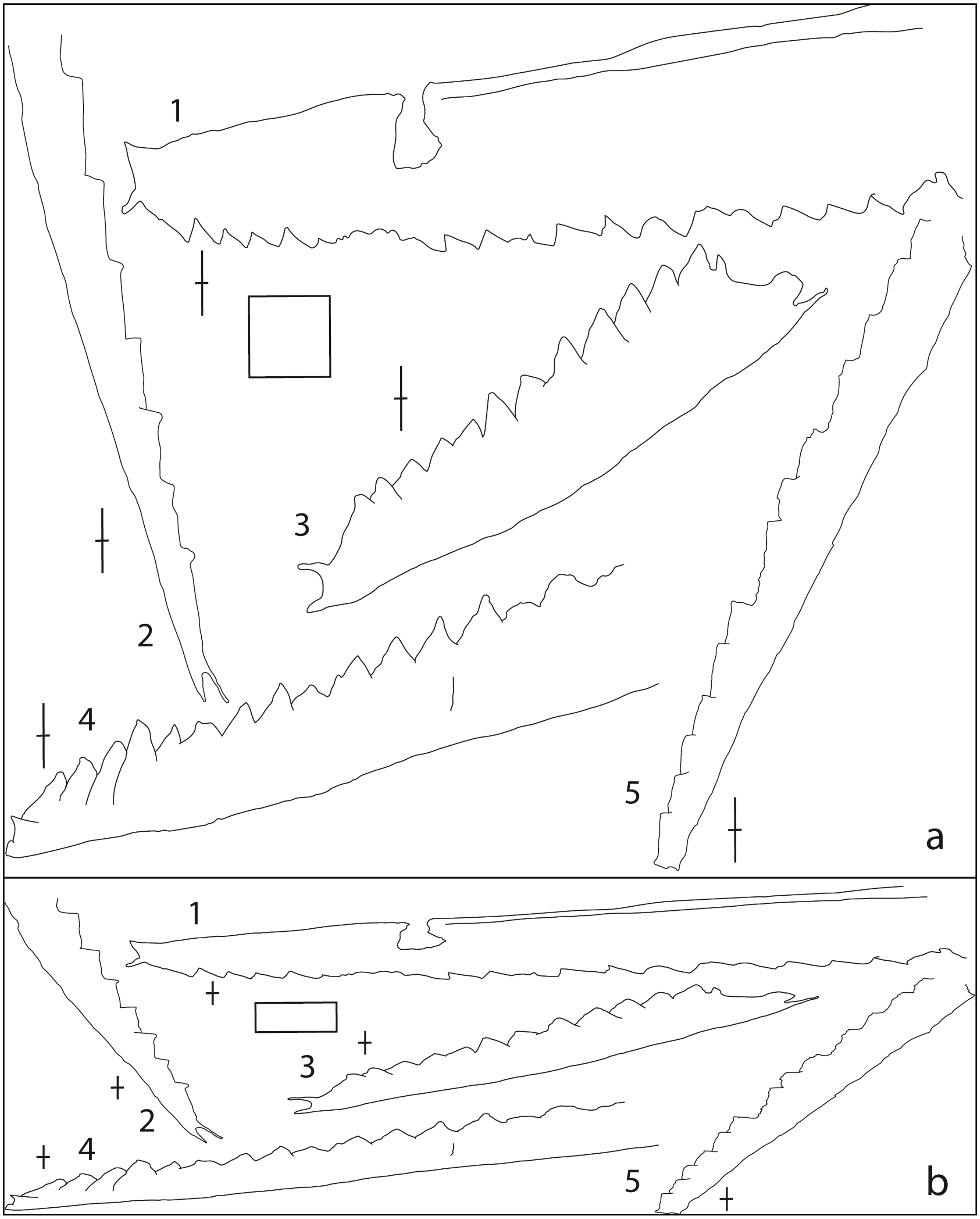

Figure 5. a) Camera lucida drawings of five graptolite specimens from two slabs that showed the same degree of tectonic strain, as determined by retrodeformation. 1 – *Pristiograptus* ex gr. *dubius*, slab 1. 2 – *Neocolonograptus parultimus*, slab 2. 3 - *Neocolonograptus parultimus*, slab 1. 4 – *Neocolonograptus parultimus*? (note incomplete preservation of the sicular aperture region), slab 1. 5 – *Neocolonograptus parultimus*? (note incomplete preservation the proximal end, but distal thecal form and dimensions match those of this species), slab 1 (this specimen was included to aid with the retrodeformation process). Elongate directions of cross symbols indicate the orientation of each specimen relative to the direction of mineral lineation. The square indicates a 2 mm scale both parallel and normal to the direction of mineral lineation. b) The same five graptolites after retrodeformation by reduction of axis parallel to the mineral lineation to 36% of original length (see text for explanation).

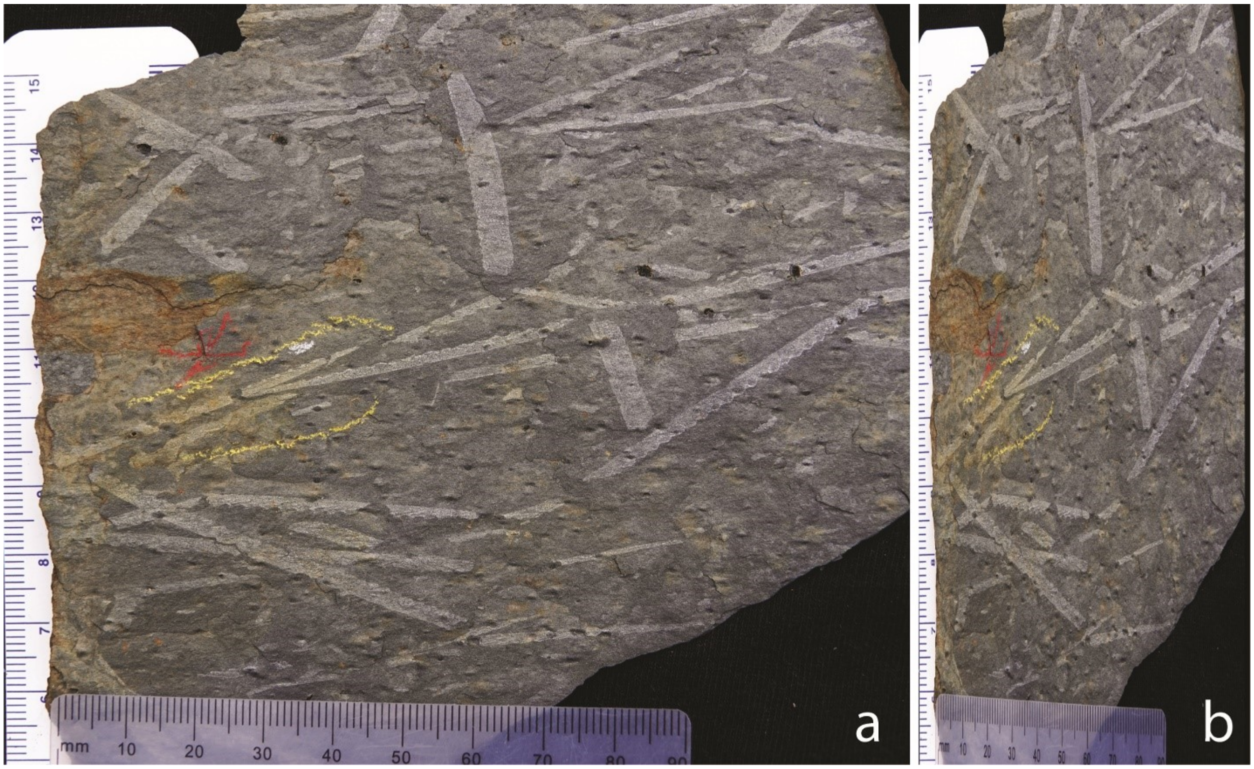

Figure 6. a) Photograph of the bedding plane of slab 1 containing all but one of the best-preserved graptolites. b) The same surface after retrodefomation by scaling the image to 36% of its original length along the horizontal axis (see text for explanation).

required a shortening to 36% of the original length along the direction of maximum extension on both slabs that showed the well-preserved specimens.

If the correct assumptions were made about the shared identity of the species, this procedure should reproduce the original, undeformed shape of the specimens. Unfortunately, however, this does not necessarily indicate that the original size of the specimens has been reproduced since there is no way to know, a priori, whether or not there was also change in length along the Y-axis of the strain ellipse in addition to extension along the X-axis. It also assumes that the X -axis of the strain ellipse is parallel or nearly parallel to the direction of the mineral lineation.

Identification and Age

The retrodeformed images of the specimens with the lobate proximal thecal apertures and the strong sicular rutella, which were originally preserved at nearly right angles to each other relative to the mineral lineation (Figs. 5b.2, 5b.3), show dimensions of rhabdosomal width and thecal spacing, as well as proximal details, that are consistent with those previously reported for *Neocolonograptus parultimus* (e.g., Jaeger, *in* Kříz et al. 1986, pp. 318-321, figs 29-34; Lenz and Kozlowska-Dawidziuk, 2004, p. 30, pl. 34, figs 12-16, 20-23, pl. 41, figs 8-12, 14, pl. 46, figs 6-8, 13). Our retrodeformed specimens show an apparent dorsoventral width of 0.85-1.00 mm at theca 1 and 1.60-1.65 mm distally and a distal two-thecal repeat distance (2TRD, Howe, 1983) of 1.9-2.3 mm. *N. parultimus* is the index fossil for the basal zone of the Pridoli and is restricted to lowermost Pridoli strata. Two additional graptolites preserved with these specimens show similar thecal dimensions and are questionably identified as *N. parultimus*. One shows slightly lobate proximal thecae but the details of the sicular aperture are not completely preserved (Fig. 5b.4) and the other shows incomplete preservation of the whole proximal end (Fig. 5b.5).

Colonograptus praedeubeli, which is late Homerian in age, shows most of the same attributes as *N. parultimus*, including the slightly lobate first few thecal apertures, slightly ventrally curved sicula with a slightly ventrally protruding virgella. However, most illustrated specimens of *C. praedeubeli* (e.g., Lenz, 1994; Koren' and Suyarkova, 1994) show a less strongly developed sicular rutellum and their proximal dorsoventral width is only 0.75-0.8 mm whereas their distal width ranges up to 1.75-2.0 mm, showing a greater degree of difference between the proximal and distal width than our material. Thus, our material is more consistent with *N. parultimus* than *C. praedeubeli*.

The single specimen that does not show the lobate thecal apertures, thecae being essentially straight tubes with slightly everted apertures throughout, or the strong rutellum on the sicular aperture (Fig. 5b.1), also shows somewhat different apparent dimensions after the same degree of retrodeformation. Its apparent width, after retrodeformation, reaches 2.0 mm by the eighth thecal pair, with a maximum of 2.5 mm distally and its distal 2TRD is 2.2 mm. This specimen is here identified as *Pristiograptus* ex gr. *dubius*. Forms meeting this general description range in age from at least lower Wenlock to lower Pridoli (e.g., Urbanek et al., 2012).

The occurrence of specimens that, after retrodeformation, meet the description and apparent dimensions of *Neocolonograptus parultimus* indicate that this collection represents an early Pridoli age, specifically the *N. parultimus* or *N. ultimus* zones (Melchin et al., 2020). This age interpretation is very different from the late Llandovery age suggested by Berry (in Roy and Forbes, 1970). However, among the taxa tentatively identified by Berry, two of the forms are species now assigned to *Pristiograptus* (the *P. dubius* group and *P. nudus*), which, as noted above, can only be distinguished by dimensions of width and thecal spacing, which is not possible in this highly deformed material without some attempt to correct for the degree and direction of strain. No specimens resembling *Monograptus priodon* were found in our collections. Forms of this species group are restricted to the late Llandovery (Telychian) to Wenlock (mid-Homerian). However, there are species of the genus *Uncinatograptus* and *Neomonograptus* occurring in Ludlow-Pridoli strata that, when poorly preserved and/or deformed, can strongly resemble forms of the *M. priodon* group. One example is *Uncinatograptus bessobaensis*, which occurs in the upper Ludlow and lower Pridoli in Arctic Canada (Lenz and Kozlowska-Dawidziuk, 2004). There are no species that would likely be mistaken species of the *Monograptus priodon* group known from the upper Homerian, the interval in which *C. praedeubeli* occurs, which supports our suggestion that this material is early Pridoli in age rather than late Wenlock.

Microfossil analysis of black shales from the new and old graptolite localities revealed the presence of poorly preserved spores for which only broad constraints of Sheinwoodian or younger and Telychian to Devonian, respectively, could be inferred (G. Machado, personal communication 2021). Although disappointingly vague, these are compatible with the basal Pridoli age for the new site, and younger than the age proposed by Berry (in Roy and Forbes, 1970).

DISCUSSION

Stratigraphic Reinterpretation

Mapping by Neuman (1967) and reconnaissance studies by Roy (1981) and Ekren and Frischknecht (1967) included early attempts to distinguish separate formations in a large area underlain by turbiditic sandstones. Reconnaissance and detailed mapping between Houlton and Lincoln in the past 40 years have improved understanding of the broad area that includes the new fossil locality (Ludman, Hopeck, unpublished mapping), but the turbidites in the region have proven difficult to separate.

These authors distinguished the Allsbury and Lawler Ridge formations by a combination of weathered color (pale orange vs gray or buff), carbonate content, feldspathic vs quartzose clasts, and the amount of intercalated siltstone and shale. However, properties purportedly characteristic of the Lawler Ridge or Allsbury are observed in numerous large outcrops without the intervening black shale. Local distinctions that can be made, e.g. feldspar-rich vs quartzose, cannot be traced for significant distances and their contacts do not yield a coherent map pattern.

As a result, the stratigraphy proposed by Pavlides (1974) and Roy (1981) has been replaced by that shown on the Bedrock Geologic Map of Maine (Osberg et al., 1985), in which rocks previously separated as the Lawler Ridge and Allsbury sandstones are now considered to be in the Madrid Formation, within which the graptolite-bearing black shale occurs as a lens. This has been confirmed and refined by our ongoing, as yet unpublished work (Figure 7). The Pridoli age of the black shale horizon supports this interpretation, as it is younger than the Llandovery to Wenlock age of the Smyrna Mills Formation, which Roy (1981) equated with the slate member of the Allsbury (Figure 7).

A more significant contact than that involving the now intraformational black shale horizon is between the basal Madrid and underlying, dominantly pelitic, Smyrna Mills Formation (Figure 7). Rocks near the contact in both formations are characterized at several places in eastern Maine by unusual oxidation states: interbedded red and green slates or black shales at the top of the Smyrna Mills and rusty weathering, pyritiferous sandstones at the base of the Madrid.

Tectonostratigraphic Implications

The original graptolite locality was discovered at the end of the geosynclinal era when the depocenter, then called the Merrimack Synclinorium, was considered to be part of the classic Appalachian eugeosyncline. The tectonostratigraphic context for the region has evolved during more than fifty years of subsequent mapping, today viewed through the lens of plate tectonics. A brief summary of evolutionary mileposts (summarized by Ludman et al., 2017) includes:

- Initially: Merrimack Synclinorium sediments thought to be derived from a western anticlinorium and from an uncertain eastern source,

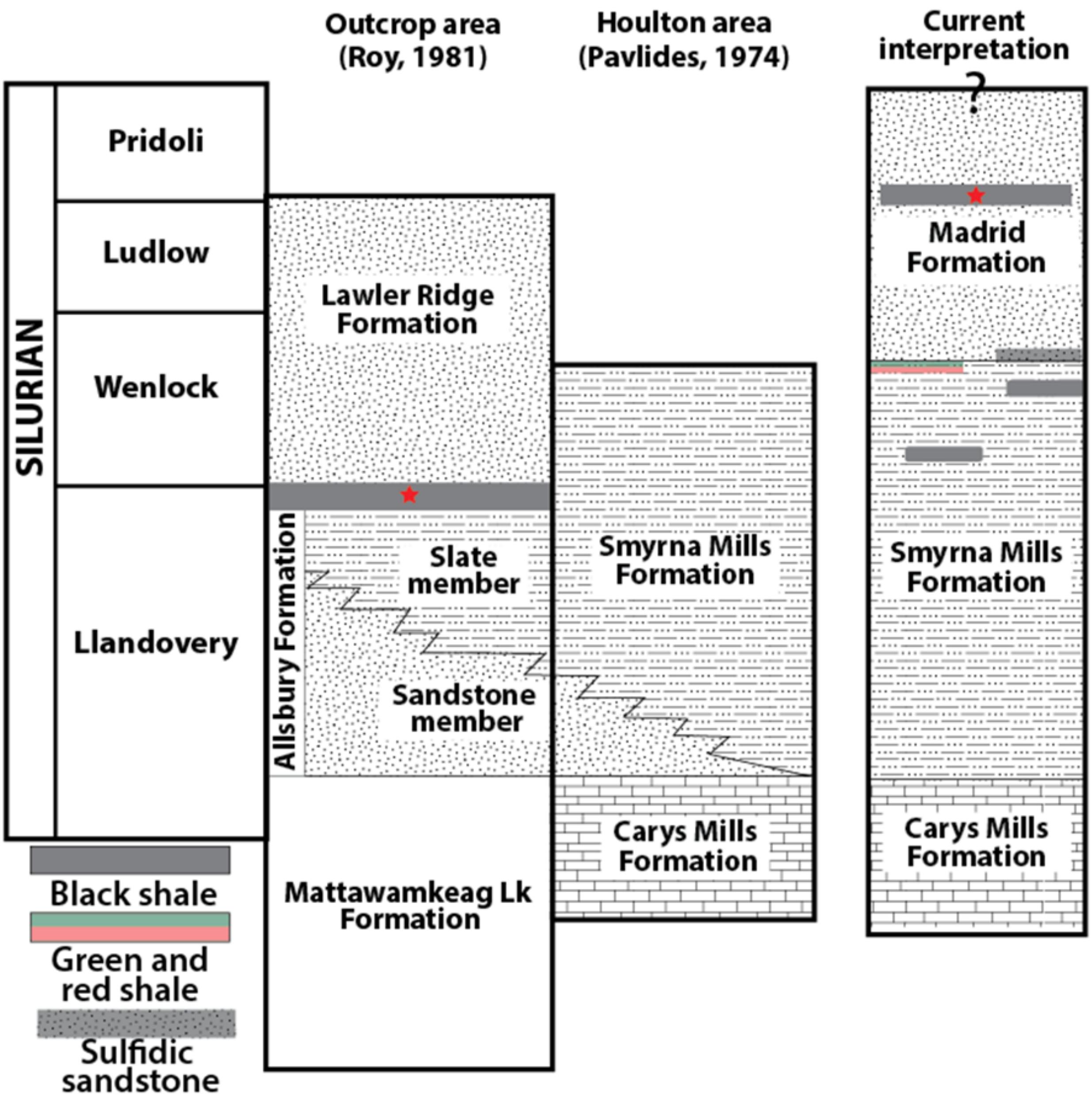

Figure 7. Interpretations of the stratigraphic position of the graptolite-bearing horizon with respect to the local and regional geology.

possibly Eastport area volcanic rocks.

- Waterville, Skowhegan, and Dover-Foxcroft units dated by graptolites and traced through folds to the western margin of the basin. Simple eastward fining sequence proposed for the western half of the basin, with Waterville area in the axial region (Ludman, 1976).
- Fredericton trough recognized as a separate depocenter, removing the Eastport area as an eastern source for what was then called the Central Maine basin.
- Cambro-Ordovician Miramichi terrane identified as eastern source of a composite Central Maine/ Aroostook-Matapedia basin (Hopeck, 1994).
- Eastern source proposed for Madrid Formation (Bradley and Hanson (2002).
- Two-phase sedimentation proposed for Central Maine/Aroostook- Matapedia basin: the first derived from local sources followed by a second in which sediments were derived from an eastern uplifted foreland bulge associated with westward migrating Acadian deformation, (Bradley et al., 2000).
- Simple two-sided sediment source model for

CMAM replaced by recognition of local emergent Late Ordovician source areas within the basin (Ludman et al., 2017).

The most likely interpretation for CMAM sedimentation is several overlapping submarine fans emanating from the marginal and intrabasinal sources. Reconstructing paleogeographic and stratigraphic relationships would be a daunting task in such an environment because of the similarity of rock types, but is made even more difficult by poor outcrop control (<1%), rare age control of stratigraphic units, and tight to isoclinal folding resulting in a *minimum* of 50% tectonic shortening (Bradley et al., 2000).

The new locality is the only reliable fossil-based age for the Madrid Formation and provides rare age control within the broad swath of CMAM sandstones. The basal Pridoli age is compatible with deposition during the second phase of sedimentation proposed by Bradley et al. (2000) and with fossils in the underlying Smalls Falls and overlying Carrabassett formations in central Maine (Ludman and Griffin, 1974).

Several unanswered questions remain.

- Among the most basic: Was the CMAM basin floored by oceanic or continental lithosphere? Turbidites and the presence of pelagic rather than benthic fauna suggest a deep-water setting, but several tectonic models envision complete subduction of oceanic lithosphere prior to CMAM sedimentation.
- What are the relationships between the Madrid and older, locally sourced Phase 1 formations?
- To what extent have early thrusts confused original stratigraphic relationships (e.g. Ludman, 2020).
- Can paleocurrent analysis and unique lithic clasts help to identify specific intrabasinal and marginal sources of CMAM sediment?

Additional fossil-based ages are needed desperately, but amphibolite facies regional metamorphism of CMAM sediments makes this approach impractical in much of southern and southwestern Maine. Graptolites and rare shelly fauna have been found in lower greenschist and sub-greenschist strata in eastern and northeastern Maine, but there have been a few attempts to use microfossils and more could prove valuable. Bradley et al. (2000) cited ages for several units in western Maine based on conodonts, and Ludman et al. (2020) were able to date others in central Maine using spores and chitinomorphs. In some instances, the fossil-based ages are not consistent with detrital zircon and other geochronologic age data (Bradley and O'Sullivan, 2016), reflecting the difficulties in comparing numerical ages with interpreted index fossil ranges.

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Maryann Malinconico estimated maximum heating temperatures for the original site based on the new stratigraphic interpretation. Microfossil samples were processed by Dr. Paulo Fernandes (Instituto Dom Luiz, Universidade do Lisbon, Portugal) and identified by Gil Machado (Chronosurveys, Almada, Portugal). AL thanks Charles Rodda for his help in collecting the samples on a hot July day, and is grateful to the Maine Geological Survey for its support during more than half a century of mapping. Ongoing funding to MJM is provided by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES CITED

Bradley, D.C., and Hanson, L.S., 2002, Paleocurrent analysis of a deformed Devonian foreland basin in the Northern Appalachians, Maine, USA: Sedimentary Geology, v. 148, no. 3-4, p. 425-447.

Bradley, D.C., Tucker, R.D., Lux, D.R., Harris, A.G., and McGregor, D.C, 2000, Migration of the Acadian orogen and foreland basin across the Northern Appalachians of Maine and adjacent areas: U. S. Geological Survey Professional Paper, Report: P 1624, 55 p..

Bradley, D., and O'Sullivan, 2016, Detrital zircon geochronology of pre- and syncollisional strata, Acadian orogen, Maine Appalachians; Basin Research, v. 29, p 571-590.

Ekren, E., and Frischknecht, F., 1967, Geological-geophysical investigations of bedrock in the Island Falls quadrangle, Aroostook and Penobscot counties, Maine: United States Geological Survey Professional Paper 527, 36 p.

Hopeck, J., 1994, Post-Caradocian strata of the Miramichi anticlinorium and their relation to the Aroostook-Matapedia belt: in Hanson, Lindley S. (editor), Guidebook to field trips in north-central Maine: New England Intercollegiate Geological Conference, 85th annual meeting, September 23-25, 1994, Millinocket, Maine, p. 43-59.

Hopeck, J., 1998, Stratigraphy and structural geology of the Wytopitlock and Springfield fifteen-minute quadrangles, eastern Maine; Ph.D. thesis, City University of New York, 160 pp.

Howe, M.P.A., 1983, Measurement of thecal spacing in graptolites, Geological Magazine 120, p. 635–638. DOI 10.1017/S0016756800027795.

Koren', T.N. and Suyarkova, A.A. 1994. Monograptus deubeli and praedeubeli (Wenlock, Silurian) in the Asian part of the former Soviet Union, Alcheringa: An Australasian Journal of Palaeontology, 18:1-2, p. 85-101, DOI: 10.1080/03115518.1994.9638768.

Kříz, J., Jaeger, H., Paris, F., and Schönlaub, H.-P.

1986. Přídolí - the Fourth Series of the Silurian. Jahrbuch der Geologischen Bundesanstalt, Wein, 129, p. 291-360.

Lenz, A.C., 1994. The graptolites "Pristiograptus" praedeubeli (Jaeger) and "Pristiograptus" ludensis Murchison) (uppermost Wenlock, Silurian) from Arctic Canada: taxonomy and evolution. Canadian Journal of Earth Sciences 31, p. 1419-1426.

Lenz, A., and Kozłowska-Dawidziuk, A. 2004. Ludlow and Pridoli (Upper Silurian) Graptolites from the Arctic Islands, Canada. NRC Research Press, Ottawa, Ontario, Canada. 141 pp.

Ludman, A., 1976, A fossil-based stratigraphy in the Merrimack Synclinorium, central Maine; in Page, L., editor, Contributions to New England Stratigraphy, Geological Society of America Memoir 148, p. 65-78.

Ludman, A., 2020, Bedrock geology of the Greenfield quadrangle, Maine: Maine Geological Survey, Open-File Report 20-10, scale 1:24,000.

Ludman, A., and Griffin, J.R., 1974, Stratigraphy and structure of central Maine: in Osberg, Philip H. (editor), Guidebook for field trips in east-central and north-central Maine: New England Intercollegiate Geological Conference, 66th Annual Meeting, October 12-13, 1974, Orono, Maine, p. 154-179.

Ludman, A., Hopeck, J., and Berry, H. IV, 2017. Provenance and paleogeography of post-Middle Ordovician, pre-Devonian sedimentary basins on the Gander composite terrane, eastern and east-central Maine: Implications for Silurian tectonics in the northern Appalachians. Atlantic Geology v. 53, p. 63-85.

Ludman, A., Machado, G., and Fernandes, P., 2020. Palynological dating of low-grade metamorphosed rocks: Applications to Early Paleozoic rocks of the Central Maine/Aroostook-Matapedia basin and Fredericton trough (Northern Appalachians) in eastern and east-central Maine, U.S.A. American Journal of Science, v. 320 #3, p. 280-312.

Marvinney, R. West, D. Jr. Grover, T. and Berry, H. 2010. A stratigraphic review of the Vassalboro Group in a portion of central Maine. In Guidebook for field trips in coastal and interior Maine. Edited by Gerbi, C. Yates, M. Kelley, A. and Lux, D. New England Intercollegiate Geological Conference Guidebook. pp 61-76.

Melchin, M.J., Sadler, P.M. and Cramer, B.D., 2020, The Silurian Period; In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M. (eds.), Geologic Time Scale 2020, Elsevier Press, p. 695-732, doi.org/10.1016/B978-0-12-824360-2.00021-8.

Moench, R.H., and Pankiwskyj, K.A., 1988, Geologic map of western interior Maine: U. S. Geological Survey, Miscellaneous Investigations Series Map, I -1692, scale 1:250,000.

Neuman R., 1967, Bedrock Geology of the Shin Pond and Stacyville quadrangles, Penobscot County Maine; United States Geological Survey Professional Paper 524-1, 37 pp.

Osberg, P.H., 1988, Geologic relations within the shale-wacke sequence in south-central Maine: in Tucker, Robert D., and Marvinney, Robert G. (editors), Studies in Maine geology: Volume 1 - Structure and stratigraphy: Maine Geological Survey, p. 51-73.

Osberg, P., Hussey, A., and Boone, G., 1985, Bedrock Geologic Map of Maine; Maine Geological Survey, Augusta, ME. Scale 1:500,000.

Pankiwskyj, K., Ludman, A., Griffin, J., and Berry, W., 1976, Stratigraphic relationships on the southeast limb of the Merrimack Synclinorium in central and west-central Maine; in Lyons, P., and Brownlow, A., editors, Studies in New England Geology, Geological Society of America Memoir 146, p. 263 -280.

Pavlides, L., 1974, General bedrock geology of northeastern Maine: in Osberg, P.H. (editor), Guidebook for field trips in east-central and north-central Maine: New England Intercollegiate Geological Conference, 66th Annual Meeting, October 12-13, 1974, Orono, Maine, p. 61-85.

Pavlides, L., 1971, Geologic map of the Houlton [15-minute] quadrangle, Aroostook County, Maine: U. S. Geological Survey, Geologic Quadrangle Map, GQ-920, scale 1:62,500.

Pavlides, L., 1968, Stratigraphic and facies relationships of the Carys Mills Formation of Ordovician and Silurian age, northeast Maine: U. S. Geological Survey, Bulletin 1264, 44 p., map scale 1:250,000.

Pavlides, L. and Berry, W., 1966, Graptolite-bearing Silurian rocks of the Houlton-Smyrna Mills area, Aroostook County, Maine: in Geological Survey Research 1966: United States Geological Survey Professional Paper 550-B, pp. B51-B61.

Pollock, S.G., 2011a, Bedrock geology of the Bangor quadrangle, Maine: Maine Geological Survey, Open-File Map 11-57, scale 1:24,000.

Pollock, S.G., 2011b, Stratigraphy and structural geology of the Bangor and Veazie 7.5' quadrangles: Maine Geological Survey, Open-File Report 11-147.

Roy, D., 1981, Reconnaissance bedrock geology of the Sherman, Mattawamkeag, and Millinocket 15' quadrangles, Maine; Maine Geological Survey Open File Report 81-46, 18 pp and 3 1:62,500 geologic maps.

Roy, D., and Forbes, W., 1970, A new silurian fossil locality on Lawler Ridge, Sherman quadrangle, Maine; in Shorter Contributions to Maine Geology, Maine Geological Survey Bulletin 23, p. 17-18.

Urbanek, A., Radzevičius, S., Kozłowska, A., and Teller, L. 2012. Phyletic evolution and iterative speciation in the persistent Pristiograptus dubius lineage. Acta Palaeontologica Polonica 57 (3): p. 589–611.

Williams, S.H., 1990, Computer-assisted graptolite studies; in Bruton, D.L. and Harper, D.A.T., editors, Microcomputers in Palaeontology, Contributions from the Palaeontological Museum, University of Oslo 370, p. 46-55.

APPENDIX: EXPLANATION OF KEY MORPHOLOGIC TERMS

Idealized image of an uncompressed specimen of *Neocolonograptus parultimus*, based on illustrations in Jaeger (in Kříz et al., 1986) and Lenz and Kozlowska-Dawidziuk (2004), annotated showing morphologic characters referred to in this paper. Note that the dorsoventral width increases with compression and the degree of flaring of the lobate thecal apertures may be enhanced by flattening as well.